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From discard to resource: unlocking the environmental and nutritional value of Bambara groundnut waste

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Introduction: Global food security is under increasing threat from population growth, environmental degradation, and climate change, highlighting the need for resilient and nutrient-rich alternative crops like Bambara groundnut. Native to sub-Saharan Africa, this underutilized legume boasts drought tolerance and nitrogen-fixing properties, making it a valuable asset for food and nutrition security. However, the processing of Bambara groundnut generates substantial waste, contributing to environmental harm, greenhouse gas emissions, and resource wastage. Current disposal methods, such as landfilling and open burning, worsen climate change and pose significant health risks to local communities.

Methods: This systematic review followed PRISMA guidelines, searching Google Scholar, Web of Science, PubMed, and Scopus (May–June 2025) for studies on Bambara groundnut waste valorization. The review identified integrated valorization pathways, challenges, and relevant case studies, providing a comprehensive analysis of Bambara groundnut waste potential.

Results: The review found that key pathways for valorization offer a number of benefits. Bioenergy production offers clean energy and reduces fossil fuel reliance. Soil amendments improve soil fertility, structure, and water retention, reducing the need for synthetic fertilizers while sequestering carbon. Bio-based materials mitigate plastic pollution and address water quality challenges. Furthermore, nutrient extraction yields dietary fiber, proteins, and bioactive compounds for food and animal feed enrichment, enhancing nutritional security and maximizing resource utilization. Case studies on legume wastes demonstrate potential for environmental, nutritional, and economic benefits.

Discussion: Widespread adoption of valorization initiatives faces multiple challenges, including technical, economic, regulatory, and socio-cultural barriers. Overcoming these necessitates collaborative efforts encompassing supportive policy measures, dedicated research, strong stakeholder partnerships, and

effective community education. Through the valorization of Bambara groundnut waste, the agricultural sector of Africa can realize opportunities for sustainable development, enhanced food systems, and economic empowerment.

KEYWORDS

food security, Bambara groundnuts, waste valorization, bioenergy, circular economy

1 Introduction

Food security still remains a burning issue globally due to the rapid increase in human population, which requires more mouths to be fed, environmental degradation, as well as the negative impact of climate change, resulting in poor crop yield. The global dependence on a few staple crops with increased dietary energy and improved global yield over the years cannot sustain the current dietary needs of man, and make food available, accessible, and affordable to the vulnerable populations (Tan et al., 2020). This heightens food insecurity and environmental strain, underscoring the need for crop diversification. Moreover, this dependence does not guarantee the nutritional quality of the food we consume. Most of these staple crops, such as cereals like wheat and maize, and tuber crops are often affected by poor-quality soil and environmental factors, which hinder their yield. This calls for more focus on alternative sources of food, which are rich in nutrients and capable of providing equity in food availability and affordability, thus enhancing food and nutrition security. This is essential if the Sustainable Development Goals (SDGs) of the United Nations on No Poverty, Zero Hunger, and Good Health and Well-being are to be achieved by 2030.

Bambara groundnut [*Vigna subterranea* (L.) Verdc.], is an underutilized leguminous crop native to West Africa, and currently regarded as an opportunity crop, due to its abundant untapped potential to enhance food and nutrition security in the context of climate change (Fredenberg et al., 2024). The legume is recognized for its adaptability to marginal environments and its nutrient-rich profile. Thriving in semi-arid regions with poor soils, this crop contributes to food security through its drought tolerance and nitrogen-fixing properties. The world's greatest producer of Bambara groundnuts (BGs) is sub-Saharan Africa (SSA). Reports have shown that the annual production of BGs in Africa is approximately 0.3 million tons, with an average yield of 0.85 t/ha. Nevertheless, the yield potential is estimated to be over 3 t/ha (Tan et al., 2020; Hillocks et al., 2012; Nedumaran et al., 2015). Nigeria produces 0.1 million tons of BGs on average, which is more than any other country. Burkina Faso comes in second with 44,712 tons, and Niger with 30,000 tons (Tan et al., 2020; Hillocks et al., 2012). The primary center of genetic diversity of Bambara groundnut is considered to be north-eastern Nigeria and Cameroon (Majola et al., 2021).

1.1 Importance and challenges of Bambara groundnut

Bambara groundnut is an income-generating and food security crop, having the ability to produce good yields in marginal soils that are poorly drained or lacking nutrients, and withstand harsh environmental conditions such as extreme heat and drought. Due to the beneficial microbes in its root nodules, Bambara groundnut cultivation does not require the use of fertilizers as it naturally fixes nitrogen in the soil. This reduces the cost of fertilizer application by

farmers and enhances agricultural and environmental sustainability. Bambara groundnut, when consumed, gives the whole complement of nutrients as the grains contain a good balance of carbohydrates, proteins, oils, and amino acids (Mohammed et al., 2023). The seeds are a valuable source of carbohydrates (~60–65%), proteins (~20–25%), fats (~5–7%), and micronutrients such as iron, potassium, and calcium, supporting their role in combating malnutrition (Khan et al., 2021). It is often intercropped with other crops such as maize, millet, sorghum, cassava, and yams because of its nitrogen-fixing roots, which aid in replenishing soil nutrients.

Despite its agronomic and nutritional benefits, Bambara groundnut remains underutilized due to limited research investment, underdeveloped markets, and cultural perceptions linking it to subsistence agriculture, particularly among women farmers (Mbosso et al., 2020). Farming systems result in the production of a huge amount of waste after processing. Leguminous crop waste is the most prevalent and includes 50% of all biomass waste, of which more than 90% is lignocellulose, with an estimated yearly global production of 200×10^9 tons (Saini et al., 2024). These agricultural wastes could be useful for the development of bio-products. A critical challenge is the management of waste streams from shells, haulms, and processing by-products of BGs which are often discarded, contributing to environmental degradation and resource loss (Nedumaran et al., 2015). Addressing these issues aligns with sustainable agricultural systems and circular economy principles.

1.2 Bambara groundnut waste as a prospective asset

Bambara by-products include the stalks, shells, haulms, and offal, which are often disposed of during processing. In Nigeria, the waste product of Bambara groundnut is the offal, which is obtained from the milling of the Bambara groundnut seeds (Tuleun et al., 2020). However, these wastes have found usefulness in biofuel production, biofertilizers, and are essential ingredients in animal feeds due to their nutritional contents high fiber content. The waste streams present opportunities for environmental and nutritional benefits. These by-products contain valuable compounds such as dietary fiber, proteins, and bioactive molecules, which can be channeled for food, feed, or industrial applications (Gulzar and Minnaar, 2017). The rich protein content of the offal makes it suitable as an alternative energy source for poultry feeds, which will reduce the cost of producing the feeds and lessen environmental degradation from the disposal of the wastes. Valorizing these materials reduces waste, mitigates pollution, and supports nutritional security. This aligns with the SDGs of the United Nations (Willett et al., 2019).

Bambara nut (*Vigna subterranea*) is a legume highly prevalent to Sub-Saharan Africa, recognized for its remarkable adaptability to

harsh climatic conditions, particularly drought-prone environments. It thrives in marginal soils with minimal inputs, making it a resilient crop suited for regions where climate change is exacerbating agricultural vulnerabilities. The seeds of Bambara groundnut are nutritionally dense, comprising high levels of carbohydrates, quality protein, crucial minerals, and fatty acids, thereby positioning it as a potential candidate for addressing food and nutrition insecurity (Mubaiwa et al., 2018).

Despite these attributes, it remains significantly underutilized when compared to other legumes such as soybean and cowpea. This underutilization extends not only to its seeds but also to the crop's by-products and residues generated during harvesting and processing. The primary wastes include shells, haulms (stems and leaves), and other residual biomass. In many rural areas, these waste products are thrown, burnt, or left to degrade, resulting in environmental deterioration, greenhouse gas emissions, as well as lost economic possibilities.

In the wake of growing global awareness around sustainable food systems, climate change mitigation, and resource efficiency, the concept of waste valorization has gained prominence. Waste valorization is the process of transforming waste resources into more usable commodities, including energy, bio-based materials, soil amendments, and nutritional supplements. When applied to Bambara groundnut, such strategies present an opportunity to enhance the crop's value chain, minimize environmental impact, and improve livelihoods, especially within the operational zones of the International Institute of Tropical Agriculture (IITA).

The circular economy framework offers a transformative lens through which Bambara groundnut waste can be viewed, not as refuse, but as a valuable input into new production cycles. By harnessing these by-products for bioenergy, compost, bioplastics, and food or feed additives, it is possible to contribute simultaneously to environmental sustainability and nutritional security. This chapter explored integrated valorization pathways for Bambara groundnut residues and outlined the enabling conditions required for their successful implementation.

This review is focused on Africa, particularly regions within the operational scope of the International Institute of Tropical Agriculture (IITA), headquartered in Nigeria. IITA's extensive collection of over 2,000 Bambara groundnut accessions facilitates research into genetic diversity and sustainable practices (Olanrewaju et al., 2022). By focusing on these regions, this article explores localized strategies for waste valorization, enhancing food security and environmental sustainability in African agricultural systems.

2 Methodology

2.1 Search strategy

To guarantee an open and repeatable systematic review procedure, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was adhered to. The primary objective of this research was to methodically find, assess, and compile the body of knowledge regarding the processes for repurposing Bambara groundnut (*Vigna subterranea*) waste. The following significant electronic databases were thoroughly and methodically searched: Google Scholar, Web of Science, PubMed, and Scopus. The search was conducted between May and June of 2025, starting from the beginning of each database and ending on the search date. The search strategy

was developed by combining terms related to the crop, its waste products, and the valorization processes using Boolean operators (AND, OR). The specific search string used across the databases was: ("Bambara groundnut" OR "*Vigna subterranea*") AND ("waste" OR "residue" OR "byproduct" OR "shells" OR "husk" OR "pods") AND ("valorization" OR "valorization" OR "bioenergy" OR "compost" OR "biochar" OR "composting" OR "biofuel" OR "biogas" OR "animal feed" OR "fertilizer" OR "circular economy"). To maximize the search's sensitivity, variations in spelling and terminology were considered, and the search was limited to titles, abstracts, and keywords where possible. To supplement the database search, a manual review of the reference lists of included articles and relevant review papers was conducted (backward and forward citation searching) to identify any additional studies not found in the initial search.

2.2 Study selection and eligibility criteria

To make it easier to eliminate duplicates, all of the records that were found during the search were exported to the EndNote reference management tool. Following that, a stringent two-stage screening procedure was put into place, as shown in the PRISMA flow diagram (Figure 1). All retrieved titles and abstracts were screened by two independent reviewers during Stage 1, and any study that at least one reviewer thought might be pertinent moved on to the following phase. A third, senior reviewer or discussion was used to settle disagreements among the reviewers. All articles that passed the first screening were retrieved in full, and their eligibility was evaluated using predetermined inclusion and exclusion criteria in Stage 2. Original research, review articles, and book chapters that specifically address the valorization of Bambara groundnut waste and are published in English from the start of each database to the present were required for inclusion. Editorials, conference abstracts lacking complete papers, non-peer-reviewed articles, studies in which Bambara groundnut waste is not the main focus of valorization, and publications that are not fully available were all excluded.

2.3 Data extraction and synthesis

A standardized data extraction sheet was created by methodically extracting and organizing data gathered from preferred publications. The following crucial data were taken from every study: key findings about the environmental, nutritional, or economic benefits; the authors' methodological details and limitations; the author or authors and the year of publication; the type of publication; and the particular valorization method studied, such as the production of biochar, composting, or animal feed. Following extraction, the data were narratively synthesized and arranged according to the pathways of valorization, such as bioenergy, agriculture, and animal feed. This approach allowed for a clear and organized summary of the current state of research and the various opportunities for Bambara groundnut waste valorization.

2.4 Quality and risk of bias assessment

The quality of each included study was evaluated to ensure the validity and reliability of the synthesized results. The checklist was

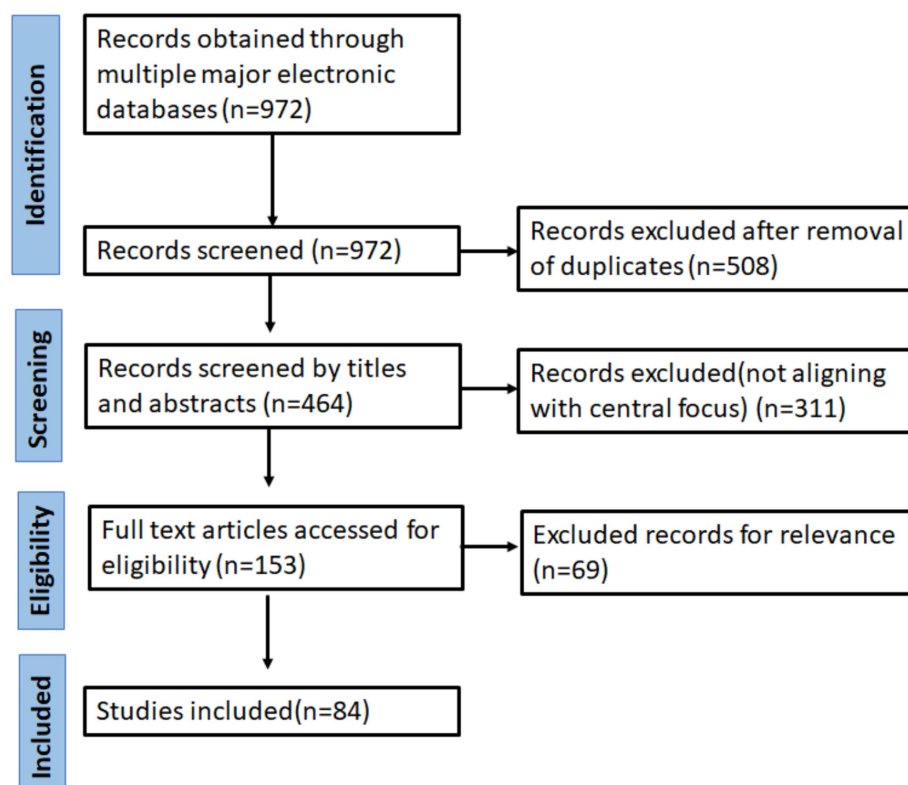


FIGURE 1
A PRISMA flow diagram of the methodology adopted for the systematic review.

adapted from the Joanna Briggs Institute's (JBI) Critical Appraisal Checklists. The clarity of the study's goal, the suitability of the experimental design and methodology, the results' clarity, the suitability of the conclusions reached, and any possible conflicts of interest were the main topics of the quality assessment. Additionally, the risk of bias was evaluated, taking into account publication, reporting, and selection bias. The final discussion, which presented the findings of the review with due consideration for the caliber of the supporting evidence, was informed by the critical evaluation of the quality and risk of bias assessment results, which were interpreted in light of each methodological strengths and limitations of the study.

3 Current environmental impacts of Bambara groundnut waste

Maintaining a pristine environment is paramount, as our planet is the only one we can inhabit and rely upon. Unfortunately, human activities are significantly accelerating waste accumulation, encompassing everything from organic and plastic materials to industrial byproducts. A foundational step toward fostering a sustainable existence on Earth involves mitigating this escalating waste problem. While the complete eradication of certain waste streams like plastics, electronic waste, and other industrial refuse presents considerable challenges, the effective management of organic waste offers numerous opportunities during disposal. These opportunities extend beyond mere reduction, encompassing the potential to transform these discarded materials into eco-friendly

products of significant economic interest, thereby promoting both environmental stewardship and sustainable development.

However, it is crucial to recognize that current approaches to waste disposal impose considerable ecological pressures. These pressures are primarily influenced by several factors: the sheer volume of waste generated, its original point of generation, the specific types of organic waste involved, and the timing of its generation—whether during the dry or wet seasons, as environmental conditions vary. Presently, numerous landfills and open waste disposal sites are in operation, often without adequate consideration for their far-reaching impacts on both human livelihoods and overall environmental health.

Within these anaerobic environments, organic matter decomposes, releasing considerable amounts of methane. This is a potent greenhouse gas with a far greater global warming potential than carbon dioxide, which is also released during the incomplete combustion of some discarded wastes over shorter timeframes. Open burning of waste materials concurrently pollutes the atmosphere directly. This combustion liberates harmful particulate matter, carbon monoxide, other greenhouse gasses, and toxic compounds. This leads to localized air quality deterioration, contributes to smog, and poses serious respiratory and cardiovascular health risks to nearby communities. Therefore, seeking alternative means of waste management appears to be the sole viable path for a better and more sustainable environment. After all, waste generation is an unavoidable aspect of human activity; however, its management is paramount.

This leads us to the transformative principle of “from waste to wealth”—quite simply, the way forward. By adding value to a material, irrespective of how seemingly worthless it may appear, it transforms

into a valuable commodity, generating economic gains. Value addition represents the new strategic approach for converting waste into economic products. This ensures the materials are no longer left to decompose on the Earth's surface; instead, they are actively removed to create economic value. Bambara groundnut waste, in particular, presents a useful economic material for establishing a value chain that can lead to wealth and prosperity, especially among smallholder farmers, traders, and crop processors.

Annually, substantial quantities of Bambara groundnut waste are produced, contributing to a growing landfill burden. More than 300,000 tons of Bambara are thought to be produced annually throughout Africa (Majola et al., 2021). Although the majority of Bambara nuts are produced in sub-Saharan Africa, West Africa is the core of production in this region. In Nigeria, for example, there are reports that production has reached over 100,000 tons, thus making it Africa's primary producer of the underutilized crop (Tan et al., 2020; Fredenberg et al., 2024). This information thus suggests that Bambara generates a significant volume of waste annually, particularly in key producing regions like Nigeria. The majority of the wastes generated range from plant stalks, residues from processing, haulage, offal, which include broken or damaged seeds, and the shells and husks, which are usually lignocellulosic and high in fiber. The disposal of these materials presents a significant challenge, which often leads to them being deposited in open dumps and landfills. Their decomposition over time releases potent greenhouse gases, such as methane. The continuous influx of such agricultural waste rapidly consumes available landfill space. In metropolitan areas like Lagos, Benin, Onitsha, Kano, Kaduna, and Enugu, the challenge of availability of spaces for siting landfills is ever becoming slim. Moreover, securing new landfill locations is often met with strong public opposition owing to concerns over environmental pollution, health risks, and land devaluation, making effective waste management a perpetual urban and rural challenge across the continent (AUDA-NEPAD, 2021; Compost Connect, 2023).

When unmanaged in open landfills, Bambara groundnut waste consistently produces greenhouse gases. The primary culprit is methane, which forms as these wastes decompose due to microbes in oxygen-deprived conditions. Incomplete combustion from burning Bambara groundnut waste releases carbon monoxide and other pollutants, including volatile organic compounds (VOCs). These VOCs are human-made chemicals with high vapor pressure and low water solubility. The release of strong greenhouse gases like carbon monoxide and methane traps heat in the atmosphere, leading to a rise in global temperatures. This temperature increase, in turn, accelerates the melting of Arctic ice, significantly contributing to higher sea levels. A substantial increase in sea level can impact ocean currents, which in turn typically influence global climatic conditions and patterns. Consequently, a significant and sustained global rise in temperature is fundamentally linked to global climatic change. Also importantly is the release of particulate matter (PM_{2.5}). Beyond environmental degradation, these waste disposal practices inflict severe adverse health effects on nearby communities, ranging from respiratory disorders (Torres-Duque et al., 2008) to heart diseases (American Heart Association, undated). Compounding these threats, the presence of carcinogens like dioxins and polycyclic aromatic hydrocarbons in burn emissions elevates the risk of various cancers among exposed

populations (Human Rights Watch, 2017; Prevent Cancer Now, 2009). Therefore, the paradigm shift from merely disposing of waste to actively pursuing “waste to wealth” strategies, which involve adding value to discarded materials like Bambara groundnut waste for economic gain, is not only environmentally imperative but also crucial for safeguarding public health and fostering sustainable development.

Beyond the direct environmental harms, current waste disposal practices lead to a significant Loss of Beneficial Nutrients and Squandered Resource Reclamation. Critically, the removal of organic matter and essential nutrients from the agricultural cycle, rather than their natural return to the soil, depletes soil fertility over time. This depletion consequently drives an increased reliance on synthetic fertilizers to maintain crop yields. Moreover, this waste represents a considerable loss of economic value. Converting these by-products into valuable commodities like compost, biochar, or bioenergy could generate substantial alternative income streams for farmers and local communities, thereby fostering a more sustainable and economically viable agricultural system. The continuous removal of organic matter and nutrients from the agricultural cycle, instead of their beneficial return to the soil, perfectly illustrates the shortcomings of a linear economy. This approach fundamentally misses a crucial opportunity for efficient environmental management within a circular economy framework. In a linear model, resources are extracted from the environment, processed into products, consumed or utilized, and then ultimately discarded as waste. This is particularly evident when agricultural residues, such as Bambara groundnut stalks and shells, are simply sent to landfills or burned, and processing by-products are washed away or otherwise discarded. Given that these are organic materials, valuable nutrients—the very building blocks for soil improvement and a sustainable factor for food security—are simply lost from the system.

On the other hand, by extending the life of resources, a regenerative economy seeks to reduce waste as well as optimize resource use. Under this model, agricultural by-products are not viewed as waste but are instead channeled back into valuable resources. This perfectly embodies the “waste to wealth” principle.

4 Potential valorization pathways integrating environmental and nutritional perspectives

The issues concerning waste generated during production are highly relevant. Consequently, the importance of waste valorization is paramount, as it serves as a dual-purpose strategy: generating economic gain for human populations while providing significant benefits for the environment. Imagine a scenario where wastes are also used as feedstock for the generation of the same products for which primary raw materials would be required. That would reduce reliance and thus help manage exploitation. The aim of this section is to explore specific pathways that not only mitigate environmental harm but also leverage the inherent nutritional components of Bambara groundnut waste for resource recovery and benefit. The concept of waste valorization, which effectively manages waste streams, is important particularly for mitigating environmental impact, reducing greenhouse gases, and enhancing soil conditions through soil nutrient amendments (Ufitikirezi et al., 2024).

4.1 Bioenergy production from Bambara groundnut waste

In a world already grappling with the threats of over-reliance on fossil fuel-based energy, alternative sources are crucial. Such sources should not only be sustainable, relying on readily available organic materials, particularly wastes, but also generate substances less detrimental to the environment than their fossil-fuel counterparts. Given this, encouraging reliance on the wastes generated from the production, processing, and consumption of Bambara groundnut is highly beneficial, emphasizing both environmental gain and the nutritional value of these by-products.

One of the most promising uses for Bambara groundnut residues lies in bioenergy generation. The lignocellulosic content of their haulms and shells makes them highly suitable for anaerobic digestion and bioethanol production. Anaerobic metabolism, the microbial decomposition of organic material in the absence of oxygen, produces biogas (mostly carbon dioxide and methane) and digestate. The biogas can then serve as a clean energy source for cooking or electricity, while the digestate can be applied to agricultural fields to enhance soil fertility (Holm-Nielsen et al., 2009).

In a study on Valorization of agro-industrial wastes for biorefinery process and circular bioeconomy, Yaashikaa and Kumar (2022) showed the relevance of Bambara in the development of strategies for generation of biogas. They reported that Bambara possessed adequate nutrients (fat and carbohydrate) for biogas generation. Moreover, Bambara groundnut waste is known for its high crude protein and nitrogen levels, making it suitable for developing biofertilizers that can provide adequate nitrogen to the soil. During this process, while carbon is converted to methane, essential plant nutrients—such as nitrogen, phosphorus, potassium, and micronutrients—remain in the digestate. Crucially, these nutrients are often in a more plant-available form (e.g., ammoniacal nitrogen) compared to raw organic matter, making them highly effective as a bio-fertilizer.

Production of bioethanol from the fermentable sugars extracted from Bambara groundnut shells offers another route for renewable energy. Technologies such as simultaneous saccharification and fermentation (SSF) can be employed to maximize ethanol yield. These bioenergy solutions align with global efforts to lessen reliance on fossil fuels, mitigate carbon emissions, and promote rural energy self-sufficiency.

Another specific study on Bambara nut chaff in the production of biogas was reported by Ofoefule and Onukwuli (2010). Ofoefule and Onukwuli (2010) also supported claims on Bambara waste suitability for anaerobic digestion and the general nutrient content of organic waste for biogas production. However, while it found blending, as most times required, did not significantly improve biogas yield, they reiterates that potentially, all organic waste materials contain adequate quantities of the nutrients essential for the growth and metabolism of anaerobic bacteria in biogas production.

Orok et al. (2024) emphasize that anaerobic digestion of Bambara wastes produces methane, which is a major combustible constituent in biogas, in addition to carbon dioxide. Anaerobic digestion directly tackles landfill issues by diverting significant volumes of organic waste, thereby preventing methane emissions that would otherwise occur in dumps. The process yields a nutrient-rich digestate—the liquid and solid residue left after digestion—along with biogas. The resulting biogas and organic fertilizer generated from anaerobic

digestion can economically offset challenges associated with the process. Notably, applying digestate back to agricultural land replenishes soil fertility, reduces the need for synthetic fertilizers, and indirectly supports the nutritional quality of future crops by ensuring healthy soil. This effectively completes a circular nutrient loop.

4.2 Soil amendments from Bambara groundnut waste

Ikhajiagbe et al. (2024) used a bio-organic fertilizer derived from food waste to enhance the growth, resilience, and yield of *Amaranthus hybridus*. Additionally, Ikhajiagbe et al. (2017) reported improved remediation and plant growth indices for oil-polluted soil after it was amended with plastic waste-prepared compost. They also noted improved growth in okra (*Abelmoschus esculentus*). Composts are typically generated through the aerobic decomposition of organic materials. The application of soil amendments enhance soil physicochemical characteristics, improving its structure, organic content as well as microbial population. Compost is one of most prominent materials for soil improvements (Food and Agriculture Organization of the United Nations (FAO), 2025). According to the TNAU TNAU Agritech Portal (2025), application of composts improve the physical, chemical and biological properties of the soil, thus sustaining soil fertility. Apart from soil fertility, application of amendments have been reported to enhance remediation of contaminated and degraded soils. Composting plays a pivotal role in sustainable waste management by addressing several critical environmental concerns, including the diversion of large volume of wastes from collection centers, landfills, open dumpsites, as well as homebased collection points (Britannica, 2025; US EPA, 2020).

Composting is a low-tech, low-cost valorization pathway especially suited to rural communities. When properly composted, Bambara groundnut shells and haulms decompose into humus-rich organic matter that can be applied to soils to improve their chemical, biological, and physical properties. Waqas et al. (2023) reported that composts from leguminous residues are typically rich in nitrogen, potassium and phosphorus. These elements are central to soil microbial activity and plant growth. In regions suffering from soil degradation, organic amendments derived from Bambara groundnut waste can restore soil fertility, lessen dependence on synthetic fertilizers, and enhance water retention. Moreover, composting contributes to carbon sequestration and provides a means of managing agricultural waste sustainably.

Composting, through its controlled aerobic decomposition, is highly effective at preserving the nutritional value of organic materials. During this process, nearly all of the initial essential plant nutrients, such as major macronutrients like Nitrogen (N), Phosphorus (P), and Potassium (K), alongside crucial micronutrients (e.g., iron, manganese, zinc, copper), are retained (Ikhajiagbe et al., 2017; TNAU Agritech Portal, 2025). What sets composting apart from simply discarding raw organic waste is its ability to transform these nutrients. It breaks down complex organic compounds into simpler, more stable structures. This vital change ensures that the nutrients become progressively more accessible for absorption by plants over time, providing a sustained release rather than a sudden flush. Organic materials, such as Bambara groundnut haulms, shells, as well as foliage, constitute a significant portion of municipal solid waste. By

channeling these materials to composting facilities instead of landfills, we dramatically reduce the sheer amount of refuse that needs to be buried.

Pyrolysis, a process used to convert certain organic wastes into biochar, offers an alternative to composting. The potential of Bambara groundnut shells for biochar production has been explored (Jatuwong et al., 2025), with research providing insights into their elemental composition and ideal pyrolysis parameters. Biochar, a carbon-rich and highly porous material, is well-established for its ability to enhance soil fertility and promote crop productivity. Furthermore, in addition to its direct benefits for soil health, biochar serves as a long-term carbon sink, contributing to environmental sustainability. It sequesters atmospheric carbon for centuries, sometimes even millennia, thereby aiding in the mitigation of greenhouse gas emissions. Consequently, biochar is a vital tool in developing resilient and sustainable agricultural systems better equipped to adapt to the impacts of a changing climate. Moreover, biochar has been successfully applied to enhance crop resilience and nitrogen use capacity in bananas (Ikhajiagbe and Ebinum, 2022).

Utilized as substrates for soil amendments, organic wastes, including Bambara, are capable of playing pivotal roles in: improving crop growth and resilience in stressed environments (Ikhajiagbe et al., 2014); supporting soil remediation efforts (Ikhajiagbe and Anoliefo, 2011; Ikhajiagbe and Mshelmbula, 2016); and enhancing soil structure, thereby stimulating the soil seed bank and consequently promoting weed biodiversity (Ikhajiagbe and Anoliefo, 2012; Ikhajiagbe et al., 2014).

4.3 Bio-based materials

Lignocellulosic biomass, such as Bambara groundnut shells, can be processed into bio-based materials, including bioplastics, biochar, and adsorbents for water treatment. The cellulose and lignin components in the shells can be extracted through chemical or thermal processes and used to synthesize biodegradable plastics. This innovation is gaining momentum as societies seek to reduce plastic pollution and transition to sustainable packaging materials (Adetunji and Erasmus, 2024). In environmental applications, pyrolyzed Bambara groundnut shells can serve as adsorbents to remove heavy metals or organic pollutants from water. This low-cost solution is particularly relevant in resource-limited settings where access to clean water remains a challenge.

4.4 Nutrient extraction for food/feed applications

Bambara groundnut residues are not merely waste; they contain nutritionally significant compounds that can be extracted for food and feed enrichment. Defatted shells, for example, retain high levels of dietary fiber and polyphenolic antioxidants (Adebowale et al., 2005). These can be processed into dietary supplements or incorporated into animal feeds to improve digestibility and health outcomes.

Furthermore, recent advancements in food science allow for the extraction of protein hydrolysates, peptides, and phytochemicals from agricultural residues. These bioactive components can function as anti-inflammatory, antioxidant, and antimicrobial agents, enhancing

the nutritional value of processed foods or animal feeds. By adopting a cascading use model—where higher-value products such as food additives are extracted before composting or energy recovery, communities can maximize the utility of Bambara groundnut waste streams.

The shells of Bambara groundnuts, which are frequently thrown away as waste, are rich in nutrients and can be utilized for a variety of things, including animal feed. They may include health-promoting substances and are high in fiber, especially pectin. The major product of processing Bambara nuts is flour, which is then cooked and eaten by the Ibo people of Nigeria in a dish known as “okpa” (Aregheore, 2001). To make the flour, the seeds are split in an attrition mill, the loosened testa are winnowed, and the cotyledon is covered with fine flour by repeatedly milling it in a hammer mill or any other kind of mill, followed by sieving it through sieves. When Bambara nuts are processed, a sizable amount of their inedible component is thrown away as trash. This inedible part had been used as soil waste and given to animals without discrimination. Weaner pigs can withstand up to 10% of toasted Bambara groundnut offal in their diet, according to a 2007 study by Onyimonyi and Okeke (2007). The accessibility of Bambara waste as a possible feeding ingredient in the diets is guaranteed by the fact that “okpa” is still a staple protein meal in the majority of Eastern Nigerian households.

An important feed component for rabbit nutrition in Nigeria is raw Bambara groundnut waste, a by-product of processing Bambara groundnut (*Vigna subterranea*). It is appropriate for use in cattle diets because it provides a reasonably high source of protein with a crude protein concentration of 16–17%. Because of its nutritional richness, accessibility, and affordability, it is frequently used as a baseline or control diet component in experimental studies looking into alternate sources of rabbit feed (Ani, 2007). The viability of feeding rabbits Bambara groundnut waste has been investigated in a number of research. According to Ani (2007), up to 30% of raw Bambara groundnut waste was added to rabbit feed. Results showed that growth performance was unaffected by inclusion rates as high as 20%, suggesting that the waste could be a good partial replacement for conventional feed ingredients like soybean meal or maize. However, performance decreased when inclusion levels surpassed 20%, possibly as a result of dietary imbalances or the presence of anti-nutritional substances (Amaefule et al., 2011).

In a separate study, Amaefule et al. (2011) investigated using raw Bambara groundnut offals to replace maize offals in a complete rabbit diet. The results were promising, as the offals could be incorporated at up to 20%. When compared to the control diet that contained maize offals, all experimental diets showed better growth performance. Notably, the diet that included 15% Bambara groundnut offal produced the greatest growth enhancement, with the growth rate rising by 58% compared to the control group. This noteworthy improvement demonstrates the potential of Bambara groundnut offal as a feed element that could increase rabbit farming output in addition to being a reasonably priced alternative (Rehman et al., 2017). These reviews lend credence to the notion that Bambara groundnut waste and offals may be essential for raising feed efficiency and lowering feed expenses in rabbit production systems, particularly in areas with expensive or limited feed supplies. But it is also critical to take into account things like the balance of the diet, potential anti-nutritional substances, and the necessity of processing (such drying or heat treatment) to increase nutrient availability and digestibility.

5 Nutritional composition of Bambara groundnut waste streams

Provide a concise overview of the potential nutritional composition found within the various waste streams produced from Bambara groundnut. Specifically, outline the primary constituents present in shells (e.g., fiber, minerals), haulms (e.g., protein, fiber), and processing leftovers (e.g., remaining protein, carbohydrates, micronutrients). This overview should establish the initial nutritional value contained in these by-products before examining possible extraction or improvement techniques in later parts.

5.1 Overview of BGs waste streams

Bambara groundnut processing generates substantial waste, including shells, haulms, and processing residues such as seed coats and milling by-products called offals. Though traditionally underutilized or discarded, these wastes are nutritionally rich, which makes them valuable for food and inclusion in animal feeds and other bio-based products. Rather than discarding the shells after harvesting the nuts, it could be channeled to other beneficial uses. Huge amounts of biomass waste are produced by agricultural industries, which can be utilized for the production of biological products and polymer compounds that will advance sustainable technologies (Aliotta et al., 2021).

5.2 Primary constituents of waste streams

Bambara groundnut shells (BGS) are primarily composed of dietary fiber, which supports digestive health in food or feed applications. The BGS are naturally lignocellulosic, consisting of a polymer of cellulose (42.4%) and hemicellulose (27.8%), lignin (13%), and a minor proportion of extractives (16.8%) (AUDA-NEPAD, 2021; Compost Connect, 2023). The BGS is also composed of a considerable quantity of volatile matter (69.1%) and low moisture (4.4%). The low moisture content is significant for the usefulness of BGS for polymeric composite development since high moisture impairs the properties of fabricated composites by reducing the strength of the bonds at the edge of the matrix, which could destabilize the dimensions, thereby making the mechanical properties of the composites of low quality (Ncube et al., 2024).

Yang and Lü (2021), observed that the proximate analysis before and after the treatment of BGS with *Pleurotus ostreatus* oyster mushroom showed an elevation in crude fiber 52.32 vs. 28.8%, crude protein 9.30 vs. 11.03%, ash content 10.90 vs. and 13.50%, fat and oil content 3.78 vs. 3.78%, respectively. The BGS had high amounts of crude fiber and ash content before the treatment, which increased with the addition of 10 g of *P. ostreatus* spawn. The BGS ash content of 10.9% observed before treatment was slightly higher from the 8.4% obtained in the study of Ncube et al. (2024). The offal from the milling of the seeds is composed of 17.90–21.16% crude protein, 5.29–21.50% crude fiber and 12.44 MJ/kg gross energy (Tuleun et al., 2020).

Rich in crude protein (10–15%) and fiber, Bambara groundnut haulms (stems and leaves) are a viable option for livestock feed or composting (Berchie et al., 2012). They also contain secondary metabolites, such as flavonoids, with potential health benefits like

anti-inflammatory effects. Unfortunately, the leaves and chaff are often discarded, leading to environmental degradation, even though they can be blended into poultry feed, providing a much better use. These residues, often discarded during flour production or traditional food processing, can be enhanced through techniques like fermentation to improve nutrient bioavailability, making them viable for human consumption or fortified feed. Nevertheless, efforts have been made to utilize this waste in biogas production by blending with animal wastes to maintain methanogens.

6 Case studies and examples

The viability of combining environmental sustainability objectives with the recovery of important nutritional components is demonstrated by initiatives to valorize agricultural waste from legume crops such as peanut, cowpea, and soybean. These case studies shed light on tactics that might guide comparable efforts to value Bambara groundnut trash.

6.1 Soybean (“okara”) valorization

In East Asia, “okara,” the insoluble residue left over after creating soy milk or tofu—is a significant agro-industrial by-product. As a significant source of protein, soybeans are highly prized and frequently utilized in Asian desserts and cuisine (Li et al., 2012). However, a significant amount of the soybean is not used in the finished product via procedures like soy milk extraction as a result; a large quantity of “okara” is produced. Actually, about 45% of each kilogram of processed soybeans is turned into the finished product, with the remaining 55% becoming “okara” (Agyei, 2015). Because of its negative qualities, including its short shelf life, gritty texture, and bland flavor, “okara” is frequently burned or thrown in landfills despite its nutritional value. The plant-based proteins found in soybeans have a comparatively high biological value, making them a great excellent supply of dietary protein in both human and animal diets. Soy protein is economical and is a viable answer to the world’s feed and agricultural problems. Also, bioactive peptides with anticancer, antihypertensive, antioxidant, antibacterial, and antidiabetic qualities are abundant in soybean by-products like “okara.” Proteolytic enzymes are usually required to remove these advantageous peptides from the intricate “okara” matrix (Redondo-Cuenca et al., 2007; Puchalska et al., 2017).

After being processed to remove fiber and oils, soy has comparatively high protein content (40%) and is a great ingredient for food. The risk of coronary heart disease is decreased by including soy proteins in a diet that is comparatively low in cholesterol and saturated fatty acids. Along with its rich protein level, soy also has fiber, which improves glucose tolerance in diabetics and decreases fat, and beneficial isoflavones, which are important in reducing heart disease. In addition to its anti-inflammatory and anti-carcinogenic properties, the fiber in soy helps with inflammation, diarrhea, and constipation (Becker-Ritt et al., 2004). However, soy contains antinutritive substances like raffinose, phytic acid, stachyose, as well as trypsin inhibitors, which can pose some hazard. Certain antinutritional substances are disappearing as a result of technological processing (Ahn et al., 2010). “okara” is raw material that is produced as a by-product from the production of soy milk and tofu (Puchalska et al.,

2017). One ton of tofu yields approximately 1.1 to 1.2 tons of “okara,” which can reach over 3,000,000 tons annually in Asia, “okara” is mostly used as agricultural fertilizer or animal feed (Čech et al., 2022). “okara,” a high-fiber residue from soy milk production, contains a strong amino acid profile and is rich in protein (20–27% by dry matter) and fiber (52–58%). After adding “okara” to maize tortillas, they measured the amino acid composition of the tortillas and the changes in their flavor and texture at different fortification levels. Higher levels of fortification with “okara” were judged inappropriate by the expert panelists who assessed the product because of its unpleasant flavor and scent. Even when up to 10% more “okara” was added to the maize flour, there was still no discernible difference in flavor between traditional corn tortillas and tortillas enhanced with “okara.”

“okara” has been used by Japanese culinary innovators and SMEs to create value-added products in fermented drinks, health snacks, and baked goods (Du et al., 2018). Notably, meat substitutes and dietary fiber supplements made from “okara” have gained popularity in regions where consumers are concerned about their health. Methane emissions from landfilling wet biomass and organic waste are decreased by these initiatives. Furthermore, “okara” is being used more and more as a feed component for monogastric animals, which helps livestock systems use fewer resources.

Financial benefits can result in the conversion of food sector wastes, including biological waste to natural fertilizers, which can effectively lessen adverse environmental effects (Peng and Pivato, 2017). Biologically derived digestates can be applied to non-agricultural land (Ahmad et al., 2014), for example, as a top layer when municipal trash dumps are closed (Teigiserova et al., 2019) or for soil rehabilitation once they are turned into biochar. Biodegradable wastes from the food industry may also be used for refining processes, which should yield valuable goods including colorings, nutrients, enzymes, and natural acids, in addition to fertilizer and energy properties (Langyinu et al., 2003).

6.2 Cowpea husk and pod utilization in West Africa

In West African nations like Nigeria and Ghana, the cowpea (*Vigna unguiculata*) is a popular legume crop that yields a large amount of husks and pods after harvest. The whole cowpea grain is typically consumed with cereals or added to soups or stews in West and Central Africa, whereas the milled cowpeas are primarily used to produce steamed cakes or fritters (Quaye et al., 2009). In addition to the traditional famous “gari” as well as beans, the dry grains are additionally processed into cowpea flour to make “agawu” and “koos,” both of which are nutritious and a common meal in Ghana when combined with millet or maize porridge. The vitamins and mineral elements found in the roots, green pods, young leaves, and seeds provide human nutrition (Ehlers and Hall, 1998). These residues were previously burned or disposed of as waste, but national agricultural extension programs and projects run by the International Institute of Tropical Agriculture (IITA) have helped to valorize them (Singh, 2006).

The goal of value-adding initiatives is to turn cowpea shells as well as pods into animal feed, especially in dry seasons when there is a shortage of fodder. In numerous parts of the globe. A significant

source of high-quality hay for animal feed is cowpea leaves (Bationo et al., 2002; Haruna et al., 2018). Cowpea forage is an essential ingredient for livestock in Nigeria’s desert regions. Cowpea fodder production helps supply feed for both big and small grazing animals. Preparation involves drying in the sun, crushing, and pelletizing wastes into feed blocks rich in fiber and remaining protein. Because it may replenish soil fertility for subsequent non-leguminous crops cultivated in rotation with it (Carsky et al., 2002) or as an intercrop, cowpea is an important part of farming systems in many places. Green manure is made from seedlings, and organic manure is made from plant waste that remains after harvest. In addition to improving organic farming for organic production, cowpeas are used as a soil-building cover crop to assist in preventing erosion (Asare et al., 2013). Composting also enhances soil fertility, thereby supporting sustainable farming. The dual benefits of this approach—reducing waste and recovering nutrients for livestock—show its strong alignment with key environmental and food security objectives.

6.3 Peanut hull (PH) valorization

Global priorities include lowering food waste and refining human food systems’ efficiency in order to end hunger. Upcycling important byproducts, such as peanut hulls, would greatly increase the amount of food available to humans given existing land usage and resource inputs because peanuts are produced in enormous amounts and generate a lot of waste. By raising the quantity of sellable harvests, this initiative could contribute to the fight against hunger while also potentially increasing farmers’ profit margins and improving their cost–benefit ratio (Putra et al., 2023; Roy et al., 2023). Peanut production requires a lot of energy or fuel, fertilizer or other soil changes, and water, all of which contribute to substantial greenhouse gas emissions, eutrophication, and other ecological externalities that increase proportionately as farming efficiency decreases and change depending on the growing region and farming practices used globally (Nikkhah et al., 2015; Deepa et al., 2022). Due to the high percentage of peanut waste and the desire to increase the value of such a plentiful resource stream, there have been multiple initiatives to reuse peanut hulls. Peanut hulls are most commonly used in animal feed, although they can also be utilized as a dry composite material for packaging and industrial fillers. Newer sectors have also looked at the possibility of using peanut hulls for commercial filtration systems and biofuel (Perea-Moreno et al., 2018; Chatterjee and Singh, 2019; Zhao et al., 2012).

The value addition of peanut hulls to human food may have special advantages for human nutritional health. Better food and nutrition safety may perhaps be supported by an increase in the total supply of shelf-stable and nutrient-dense foods through effective retention in the human food supply. Repurposing peanut byproducts, such as hulls, for human consumption also offers farmers financial advantages since it raises the market value of peanut hulls, which can be sold for more than cheap animal fodder (Thorsen et al., 2022). Furthermore, by utilizing every part of the peanut harvest and promoting greater byproduct salvaging, the ecological impact of peanut production can be reduced, and the effects of food waste can be greatly diminished (Collins and Sanchez, 1979; Salem et al., 2022). Other nut hulls and nut by-products, such as those of coconut hull, hazelnut shells, almond,

and walnut shells, are widely known to be valued (Prakash et al., 2018; Raczky et al., 2021; Konak et al., 2023). In culinary applications, these flour substitutes contribute beneficial bioactives, raise the percentage of calories from protein, and decrease net carbs by adding dietary fiber. While often considered waste, hazelnut, almond, and Bambara shells (similar to peanut hulls) are recognized as safe for human consumption. Early development has already shown their potential in nutritional products. Notably, hazelnut hulls are already used in commercially available snack foods (Cao et al., 2024), and almond hulls have been added to bread, with consumers giving it high ratings for flavor and satisfaction (Kahlaoui et al., 2022). Furthermore, preliminary research has investigated using almond hulls to produce mycoprotein for alternative protein diets. The examples of peanut husks, cowpea leftovers, and “okara” show how the value-adding of legume by-products can have both nutritional and environmental advantages. These programs attest to the viability of combining nutrient recovery, emissions mitigation, and waste reduction in sustainable food systems. Through creative, biocircular solutions, these case studies promise both ecological and financial benefits for the value-adding of Bambara groundnut waste.

7 Policy and implementation challenges

At the moment, there is no evidence of suitable technological strategies being deployed to manage Bambara groundnut waste. Our concerns have been that agricultural engineers will enable the deployment of suitable innovations that would support the required infrastructure that would be generally acceptable to all.

As such, the Society for Underutilized Legumes (SUL), Nigeria, with its headquarters at the Genetic Resources Center, International Institute of Tropical Agriculture (IITA) has increased advocacy for the adoption of Bambara groundnut as a mandate crop in research institutions across sub-Saharan Africa, particularly in Nigeria. This is coming on the heels of the adoption of the crop by the CGIAR, as evident during the Science Week held in Nairobi, Kenya. Furthermore, foremost national research institute in Nigeria, such as the Institute for Agricultural Research (IAR), Ahmadu Bello University, Zaria, has indicated interest in leading the development of varieties that would be adaptable for the greater use and commercialization in the country and Africa as a whole.

Nigerian governmental bodies like the Federal Ministry of Agriculture and Food Security, the Ministry of Innovation, Science and Technology, and the Federal Ministry of Health, alongside non-governmental organizations, are prepared to drive essential government policies. Their aim is to foster economic incentives, boost consumer demand for sustainable and nutritious products, and ensure the availability of research and development expertise. Key research-focused agencies such as the Agricultural Research Council of Nigeria (ARCN), Nigerian Stored Products Research Institute (NSPRI), and the National Biotechnology Development Agency (NABDA) are also integral to these efforts.

Despite the scientific and practical promise of Bambara groundnut waste valorization, several challenges hinder widespread adoption. These barriers span technical, economic, institutional, and socio-cultural domains.

7.1 Technical and infrastructure barriers

The valorization processes often require specialized equipment and skilled labor, which are scarce in many rural areas. Composting can be done manually, but bioethanol production and bioplastic synthesis demand more sophisticated facilities (see Table 1). The deficiency in infrastructure for the collection of waste, segregation, as well as transportation, also limits the feasibility of centralized processing plants.

7.2 Economic constraints

Start-up costs for valorization enterprises can be prohibitive, especially for smallholder farmers. Market uncertainty around eco-products such as bioplastics and biofertilizers may deter private investment. Moreover, many communities lack access to microcredit or development finance that could enable them to establish such ventures.

7.3 Regulatory and policy gaps

In many countries, there is a lack of coherent policies promoting the circular bioeconomy. Regulatory uncertainty concerning the classification and safe use of agricultural waste for food and feed purposes can stall innovation. For instance, standards for compost quality, bioplastic certification, and food safety are often fragmented or non-existent in developing economies (Galanakis, 2021).

7.4 Socio-cultural factors

In some contexts, cultural perceptions of waste may pose barriers. Using agricultural residues in food or feed might be seen as unsafe or undesirable, despite scientific evidence to the contrary. Awareness

TABLE 1 The main valorization pathways of Bambara groundnut waste along with their associated environmental and nutritional/economic benefits.

Valorization pathway	Environmental benefits	Nutritional/economic benefits
Bioenergy (biogas, bioethanol)	Reduces reliance on fossil fuels; lowers GHG emissions	Provides renewable energy to rural communities
Composting and soil amendment	Improves soil structure and fertility; sequesters carbon	Boosts crop yields; reduces need for chemical fertilizers
Bio-based materials (bioplastics, adsorbents)	Reduces plastic pollution; treats wastewater	Creates sustainable packaging; supports green jobs
Nutrient extraction (food/feed additives)	Minimizes waste; reduces pressure on natural resources	Enhances food/feed value; offers income from by-products

Source: Francis A. Igiebor.

campaigns and community engagement are needed to shift these attitudes and promote behavior change.

7.5 Opportunities and recommendations

Despite these barriers, several opportunities can be leveraged to support the valorization of Bambara groundnut waste:

- 1 Governments can implement enabling policies such as tax incentives for green enterprises, subsidies for composting and renewable energy projects, and public procurement of bio-based products.
- 2 Institutions like IITA can play a central role in developing low-cost, scalable valorization technologies and providing technical assistance to farming communities.
- 3 Collaboration between farmers, NGOs, government bodies, and private companies can pool resources, share risks, and enhance market access for valorized products.
- 4 Training programs for farmers, processors, and extension workers on waste valorization techniques can empower communities and create green jobs.

8 Conclusion

Transforming Bambara groundnut waste into valuable resources presents a game-changing opportunity for sustainable development. This approach not only mitigates pollution and enhances soil fertility through the production of bioenergy and compost but also tackles malnutrition and supports food security by extracting nutritious compounds. Adopting circular economy principles that merge environmental and nutritional goals can revolutionize agricultural waste management in Bambara groundnut-producing regions. This dual-focus model aligns with global sustainability goals and provides a framework for resilient food systems, resource efficiency, and economic empowerment. Instead of being discarded into the environment, Bambara groundnut wastes can be utilized as valuable resources for developing bio-products. By harnessing Bambara groundnut residues for biofuel and animal feed, resource efficiency is optimized, reflecting circular economy principles. This valorization approach reduces environmental harm and boosts livestock nutrition, ultimately contributing to more resilient and sustainable food systems.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repository and accession number(s) can be found in the article/supplementary material.

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ML: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – review & editing. OO: Conceptualization, Data curation, Formal analysis, Investigation, Resources, Writing – review & editing. EO: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. BM: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. LO: Data curation, Investigation, Methodology, Supervision, Writing – review & editing. FI: Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing. AU: Formal analysis, Project administration, Writing – review & editing. TA: Conceptualization, Formal analysis, Project administration, Supervision, Visualization, Writing – review & editing. BI: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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